

PROCEEDINGS
OF THE
INDIAN ASSOCIATION
FOR THE CULTIVATION OF SCIENCE.

Conducted by
Prof. C. V. RAMAN, M.A., D.Sc.

Vol. VIII.

With Five Plates.

Printed at the Calcutta University Press, Senate House, Calcutta,
by Bhupendralal Banerjee and Published by the Indian
Association for the Cultivation of Science,
210, Bow Bazar Street, Calcutta.

1923

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Fig. 1

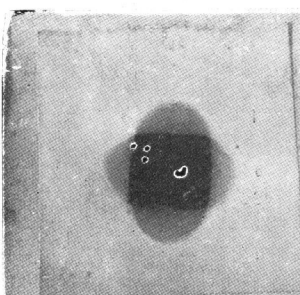


Fig. 3

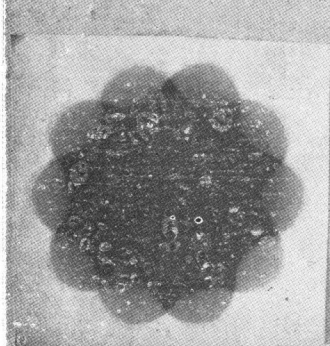


Fig. 2

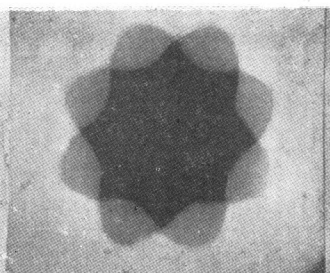


Fig. 4

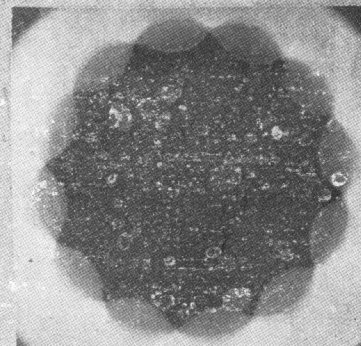


Fig. 5

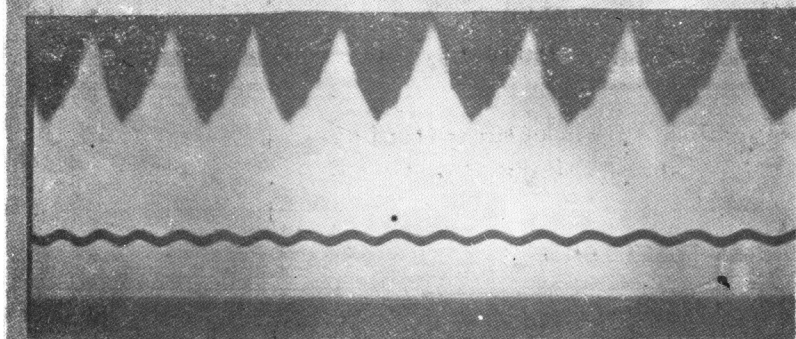


Fig. 6

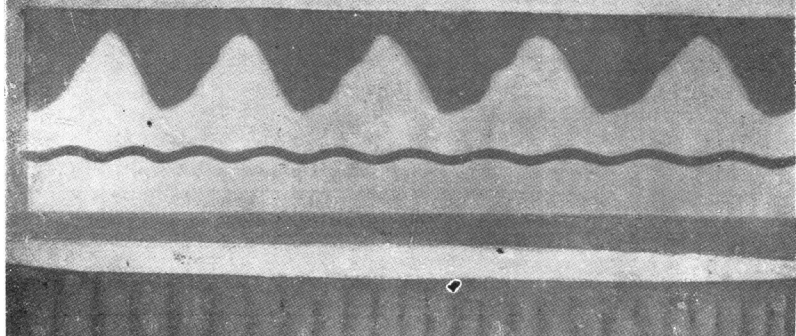
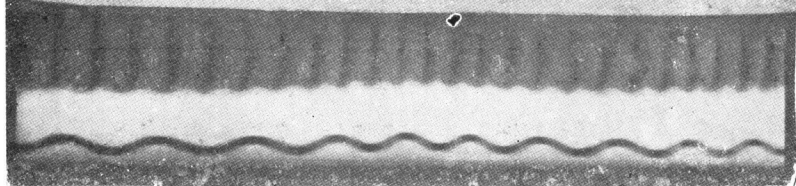


Fig. 7



V. On the Oscillations of Spheroidal Drops and the Phenomena of the Spheroidal State.

BY

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[Plate I]

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3. Determination of frequency for various sizes of drops.
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5. Explanation of the maintenance of the oscillation.

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1. Introduction.
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SYNOPSIS AND CONCLUSION.

PART I.—THE OSCILLATIONS OF SPHEROIDAL DROPS

1. Introduction.

It is well known that when the upper surface of a vibrating plate is covered with a layer of mobile liquid, the surface usually presents a beautifully crisped appearance. A full account of experiments on this

subject was given by Faraday in the Philosophical Transactions of the Royal Society, 1831. Another series of beautiful forms are observed when, instead of a layer of liquid, we take a drop which does not wet the surface and rests on it in the form of a spheroid. These seem to have been first observed by C. W. Batdorf.¹ In the present note an account is given of the quantitative study of the vibrating drops. The natural frequency of oscillation has been investigated, and it has been found that the amplitude of motion must be taken into consideration in deducing the frequency. The relation between the vertical motion of the support and the horizontal oscillation of the drop has been determined. It has been found that the maintenance falls under the class of those under forces of double frequency as in the cases discussed by Faraday where the motion of the liquid surface is vertical.

2. *Experimental Details.*

In order to study the oscillation of the drops Prof. C. V. Raman's Motor Vibrator² was used with a slight modification. The rocking lever was made to vibrate in a vertical direction. Attached to this was a watch-glass which was capable of sliding along the rod and of being fixed in any desired position; large variations of its amplitude of motion could be made by shifting the crank pin along the slot (see p. 447, Physical Review, Nov. 1919), and finer adjustments of amplitude were made by moving the watch-glass along the vibrating lever. The frequency of oscillation was kept constant by a sliding rheostat, and a stroboscopic fork. The frequency was kept constant at about 60 oscillations per second, and clean mercury drops were used.

¹ C. W. Batdorf, Physical Review, Dec. 1912.

² Prof. C. V. Raman, Physical Review, Nov. 1919.

In order to measure the diameter and the amplitude of vibration of the drop, the following arrangement was made. Light from an arc lamp was reflected through the bottom of the watch-glass, and by means of a right-angled prism, an enlarged picture was obtained on a white screen by a good lens. This arrangement is suitable for showing the phenomena to a large audience, and for photography.

When the support oscillates up and down, the drop takes the form of a peaked star, the number of star-points depending upon the frequency of vertical oscillation, and on the dimensions of the drop. The crests and troughs of the marginal wave succeed each other so quickly, that we cannot detect the different phases of the motion. Hence we observe double the number of star-points actually present. By changing the dimensions of the drop, the number of star-points may be increased, the frequency of vertical oscillation being kept constant.

Plate I shows some of the star-figures obtained. Fig. (1) represents a two-point star, photographed as a four-point one. The circular figure of equilibrium assumes an elliptical shape. The vibrating part of the drop is easily recognised by the half-shaded portion. A figure (not reproduced) shows a three-point star, the shape of the disturbed figure being an equilateral triangle. Fig. (2) shows a four-point star, the disturbed figure being a square. Figs. (3) and (4) shows five- and six-point stars in which the disturbed figures are a pentagon and hexagon respectively.

3. *Determination of the frequency of the star-points.*

To find out whether there was any definite relation between the frequency of vibration of the star-points, and that of the vertical oscillation for different cases, an electromagnetic vibrator was brought in unison with

the vertical oscillation, and its movement and that of the vibrating star-point, were simultaneously photographed as wavy curves. Figs. 5 and 6 show simultaneous records, from which it is evident that the frequency of vibration of the star-point is half that of the vertical oscillation. In this way, when by varying the diameter of the drop the number of star-points was changed, it was observed that the above relation remained true. It was also noticed that the motion of the star-points was not symmetrical and simple. The nodal points also were not places of absolute rest, but a slight regular motion was perceptible.

4. Calculation of the natural frequency of oscillation of the star-points.

The motion of the star-points is practically confined to two dimensions, and then the calculation becomes very simple by Rayleigh's method of energy. Let us represent the radius vector at any instant in the form

$$r = a_0 + \sum_1^n a_n \cos n\phi \quad \dots (1)$$

The potential energy due to capillarity from the configuration of equilibrium is given by

$$V = \frac{1}{2} \pi T (n^2 - 1) a_n^2 a \quad \dots (2)$$

where a = radius of the drop

T = surface tension

n = number of the star points

The velocity potential of the liquid motion is given by

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \phi^2} = 0$$

$$\therefore \psi = A r^n \cos n\phi \quad \dots (3)$$

where A is determined from the condition

$$\frac{\partial \psi}{\partial r} = \frac{\partial r}{\partial t} \text{ when } r = a.$$

The kinetic energy is by Green's theorem

$$T = \frac{1}{2} \rho \int \left\{ \psi \frac{\partial \psi}{\partial r} \right\}_{r=a} r d\phi$$

$$= \frac{1}{2} \rho A^2 n a^{2n}.$$

On putting the value of A we obtain

$$T = \frac{1}{2} \rho \left(\frac{\partial a_n}{\partial t} \right)^2 \frac{a^2}{n} \quad \dots (4)$$

From (2) and (4) the frequency N is calculated and found to be given by

$$4\pi^2 N^2 = \frac{T n (n^2 - 1)}{\rho a^3} \quad \dots (5)$$

Formula (5) is only true when the amplitude of motion of the star points is small. Dr. Bohr¹ has given a formula when the amplitude of motion is finite and not infinitesimal. His formula is given by

$$4\pi^2 N^2 = q^2 \left\{ 1 - \frac{a_n^2}{16a^2} \cdot \frac{(n^2 - 1)(34n^3 - 33n^2 + 50n - 18)}{(2n^2 + 1)(2n - 1)} \right\} \quad \dots (6)$$

where $q = \frac{T n (n^2 - 1)}{\rho a^3}$ approximately.

From (5) and (6) it is evident that the effect of the finite amplitude of motion is to diminish the natural frequency. Table I shows a comparison of the calculated frequencies from formulæ (5) and (6) respectively.

¹ Phil. Trans. Royal Society, Vol. 209.

TABLE I

Mercury Drops

Frequency of the vertical oscillation 60 per second

Number of star-points.	Diameter cm.	Amplitude cm.	Calculated frequency from (5).	Calculated frequency from (6).	Observed frequency.
3	·51	·08	37	29·6	30
4	·71	·07	36	31·0	30
5	1·0	·05	31	29·1	30
6	1·08	·08	36	29·1	30
7	1·32	·07	34	30·0	30
8	1·42	·08	37	30·0	30
9	1·49	·08	41	32·0	30

The frequency of the star-points should be about 30 per second, and from the table it is evident that the calculated values for formula (5) are much greater than the observed values, while formula (6) agrees well with them.

5. *Maintenance of vibration of star-points.*

The up and down motion of the support disturbs the figure of equilibrium of the drop. The simplest disturbed figure from a circle is an ellipse. This means that when there is contraction of the circular boundary in one direction, there is extension in another, and *vice versa*. As the support is moving upward, let us suppose that the liquid is also moving away from the centre of drop in a horizontal direction. At the instant when the

support is at the extremity of its upward journey, the liquid still moves outward on account of its inertia, stopping when the support is at the extremity of its downward journey. At this instant the restoring force is very large, and as the support moves upward, the liquid moves inward; this inward motion comes to an end when the support is at the extremity of its downward journey. This outward and inward motion of the liquid shows up as star-points. It is now clear from the nature of the motion of the star-points that the period of oscillation is double that of the support. It is also evident that the motion cannot be symmetrical since the inward motion is to some extent resisted, hence the oscillation curve of the star-point, see Figs. 5 and 6, is asymmetrical. The curve also shows presence of harmonics.

PART II.—THE PHENOMENA OF THE SPHEROIDAL STATE

1. *Introduction.*

The phenomena of the spheroidal state of water engrossed the attention of the early physicists whose first object was to establish whether the drop of water touched the surface of the hot plate or not. This being settled, the question arose as to how the drop is enabled to float on a cushion of its own vapour. In 1878, Johnstone Stoney¹ put forward the theory of polarised stress arising from the difference of temperature of the small gap on its two surfaces. His expression for the stress *S* is given by

$$\frac{Q^2}{PT}$$

where *Q* represents the heat conducted across the gap per second, *P* is the vapour pressure, and *T* the absolute temperature of the gap. *Q* can be calculated if the width of the gap, its area, and the thermal conductivity are

¹ British Assoc. Report, 1878.

known. Hence if Stoney's theory be correct, the width of the gap at different temperatures of the hot plate must be capable of calculation.¹ With a view to test this, the investigation of the theory of the spheroidal state was undertaken at the suggestion of Dr. Raman. The experiments resulted in establishing a definite relation between the width of the gap and the difference of temperature between the hot plate and the drop, and some interesting facts were also noted concerning the gap and the star-form oscillation of the spheroidal drop.

2. Experimental arrangements.

A simple arrangement was made for the observation of the gap. The drop rested on a polished convex plate of silver which was heated by a Bunsen burner, and is anchored by a fine wire held above it, to which the drop sticks without interfering with the phenomena at all. A powerful beam of light from an arc-lamp passes through the narrow gap between the drop and the plate, and a magnified image of the gap is focussed by a camera lens on a screen where its behaviour can be observed. All superfluous light can be cut off by suitable screens placed behind the drop. The temperature of the hot plate was noted by a thermo-couple soldered to it. The temperature of the drop almost remains constant at 95.6°C as has been shown by Batdorf,² hence the difference of temperature between the hot plate and the drop was simply obtained by noting the temperature of the hot plate, and subtracting 96°C from it.

In order to study the variation of the width of the gap with temperature, the mass of the drop was kept constant by keeping the size of the image the same on

¹ See also Maxwell's expression for the polarized stress, Phil. Trans., 1879, p. 252.

² Physical Review, Dec. 1912.

the screen. Careful measurements of the gap at various temperatures were taken, and a table was drawn up. It was found that the width of the gap was definite at a fixed temperature of the hot plate when the size of the drop was the same. Table I shows the widths of the gap at various temperature differences D .

TABLE I

Size of drop kept constant at $r = 7.5$ mm.

No.	h in mm.	$D^{\circ}\text{C}$.
1	1.25	224
2	1.40	304
3	1.60	490
4	1.50	364
5	1.40	304
6	1.25	224
7	.75	104

In the course of these experiments, it was observed that a fine droplet when thrown upon the hot plate began to jump like an elastic ball. This led to the enquiry if the spheroidal drop actually oscillates up and down in a vertical plane. This point was ascertained by photographing the gap on a moving plate. The various phases of the gap were at once evident from the picture. It was found that the gap was not stationary; but opened and closed periodically. The rate of the periodic opening and closing of the gap depends in a compound manner upon the difference of temperature between the hot plate and drop and the size of the drop. Fig 7 in Plate I illustrates the periodic closing and opening of the gap,

the simultaneous record of a style attached to an electrically maintained fork making 60 vibrations per second indicating the frequency of the motion. Since the hot plate is stationary, the closing and opening of the gap must be due to the vertical oscillation of the drop, the frequency of the latter being the same as that of the closing and opening of the gap. The asymmetrical character of the vertical oscillation of the drop is clear from the figure where the white space (when light passes freely through the gap) has a greater width than the dark space, *i.e.*, phase of obstruction to light.

It was found, however, that there are in fact two types of the spheroidal state. (1) In the first type (100° difference of temperature, more or less), the drop is stationary, no oscillation takes place, nor is any ripple motion observed on the surface of the drop, though convection currents may be visible. (2) At about 200° difference of temperature the drop begins to oscillate up and down, resulting in periodic closing and opening of the gap. Fine ripples appear on the surface, and vigorous motion of the drop sets in; sometimes the drop takes the form of an elongated spheroid, moving bodily from place to place. If this motion is stopped the drop takes a star-shaped form. Batdorf has given a complete study of these star-forms. The peaks of these star-forms vibrate in the horizontal plane, but on account of the persistence of vision the drop appears stationary. Stroboscopic observation renders the oscillation apparent. The number of these star-points, *i.e.*, the peaks observed is double the number that is actually present. The number of these star-points depends upon the temperature difference and the size of the drop. It was found that by slightly moving the burner, and thus decreasing the temperature, the peaks begin to decrease in magnitude, and then suddenly another pattern starts up, the size of the drop

remaining almost the same. If we keep the temperature constant, we obtain a series of forms in which the star-points diminish in number, as the size goes on diminishing by escape of vapour from the gap and evaporation. For the success of these experiments, distilled water should be employed, and the plate must always be clean and polished. To start the star-forms, sometimes slight coaxing is necessary. As soon as the body-motion of the drop sets in, it must be concluded that the drop will soon take up the star-form. By employing a shallow plate and a large drop, big star-forms are obtained.

3. *Theory of Spheroidal State.*

A relation between D and h can be obtained on the assumption that the whole quantity of steam formed per second escapes from the gap according to the laws of viscosity, and that the radial velocity of steam is zero at the surface of the hot plate and at the bottom of the drop. With these premises, we have the quantity M of steam escaping per second

$$M = \frac{h^3 P}{6\mu} \rho \quad \dots (7)$$

where P denotes the excess of pressure within the gap over the outside, ρ is the density and μ the viscosity of the steam. The heat conducted across the gap per second is given by

$$Q = \frac{KD}{h} \pi a^2 \quad \dots (8)$$

where K represents conductivity, and a the radius of the drop. Hence the quantity of steam formed per second is equal to

$$M = \frac{KD}{hL} \pi a^2 \quad \dots (9)$$

L = latent heat of steam.

Equating (3) and (5) we have

$$h^4 = D \left[\frac{6\mu K \pi a^2}{L P \rho} \right] \quad \dots (10)$$

Equation (10) which is dimensionally correct shows that h is proportional to D if the term in the bracket remains constant. For the same size of the drop, the term in the bracket is almost a constant; from the observed values of h and D for a given size of the drop given in Table I, a graph was drawn with h^4 as ordinate and D as abscissa. The curve is found to be accurately a straight line. Hence the difference of temperature between the hot plate and the drop is directly proportional to the fourth power of the width of the gap. The absolute value of h can be calculated from (10) by assuming that the pressure inside is greater than outside, such that $P \cdot \pi a^2$ is equal to the weight of the drop. The calculated value of h comes out a little higher, probably on account of the uncertain values of the constants in the circumstances, and moreover there is always evaporation at the surface. At any rate, we can regard equation (10) to be approximately true.

We have seen that the spheroidal drop oscillates vertically; the formation of the star-forms with vibrating peaks can now be explained in terms of the vertical oscillation. Let us recall the behaviour of a drop of mercury resting on a watch-glass made to oscillate vertically discussed in Part I of the paper. The drop takes the form of a star with vibrating peaks. The frequency N of these peaks vibrating in the horizontal plane, must be half that of the vertical oscillation N^1 , therefore

$$N = N^1/2 \quad \dots (11)$$

and the number n of the peaked points is determined by

$$n^3 - n + \pi^2 N^2 a^3 \rho / T_3 = 0^1 \quad \dots (12)$$

where T is the capillary tension, ρ the density and a the radius of the drop.

¹ Bayleigh's Theory of Sound, Vol. II, p. 355.

Table II has been drawn up from (11) and (12) showing the values of N , a and n the number of peaked points.

TABLE II
Water Drops

No.	N	a cm.	n
1	50	·74	4
2	100	·72	5
3	300	·63	6
4	50	·42	3
5	100	·57	4
6	300	·51	5
7	300	·30	3

It is observed from (1), (2) and (3) that for about the same size of the drop when the frequency of vertical oscillation is increased two times and three times, the number of peaked points increases from four to five and five to six respectively. For the same value of N , when the size of the drop is halved, the number of peaks is also halved, as shown by (3) and (7). The number of peaks is approximately proportional to the size of the drop when N remains the same.

Just as mercury drops are thrown into vibrating star forms by a vertical motion of the support, the same effect occurs in the case of spheroidal drops of water. On account of the vertical oscillation, the drop takes the form of a vibrating star. The frequency of these vibrating peaks being always half that of the vertical oscillation,

the number of the star-points is determined by the size of the drop. For a given size of the drop, when the temperature rises, the rate of vertical oscillation N increases, so also the number of star-points, as shown in Table II, and remarked above in the preceding paragraph. When the temperature remains the same, and the rate of vertical oscillation remains constant, the frequency of the star-points has the same value, but the number of star-points increases with increasing size of the drop. But when the size of the drop is increased to such an extent as to change the rate of vertical oscillation, the resulting change in the number of star-points is a complicated one and cannot be calculated from (12) as N is indeterminate, *i.e.*, the function upon which N depends in the case of spheroidal drops of water, is unknown.

The number of star-points is always an integer. Hence, when it so happens that the size of the drop is such that equation (12) is not satisfied with n an integer, fine ripples appear upon the surface, vigorous motion sets in, till the size changes by evaporation and escape of steam from the gap, and equation (12) is satisfied. Then the star-form begins at once. These ripples and body motion of the drop are also observed in the case of mercury drops oscillating vertically when (12) is not satisfied.

SYNOPSIS AND CONCLUSION.

Part I of the paper discusses the theory of the star-form oscillations of mercury drops resting upon a vertically oscillating glass plate. It is shown that the frequency of horizontal oscillation is half that of the vertical oscillation. The presence of harmonics whose frequency is $\sqrt{2}$ times that of the vertical movement is also noticed. It is shown that the large amplitudes of motion maintained in practice have a very sensible

influence on the natural frequency of the drop and must be allowed for, and that they also result in a distinct asymmetry in the oscillations.

Part II discusses the theory of the spheroidal state. It is shown that there are two types of spheroidal state, one in which the gap between the drop and the hot plate is stationary, and the second type in which the gap opens and closes periodically. The second generally obtained when the temperature of the plate is high; the drop in fact executes a vertical oscillation with a frequency which may be a few hundreds per second. If the frequency of vertical oscillation of the drop be approximately twice that of a possible horizontal oscillation, the drop commences oscillating in a star-form, in other cases its surface is merely thrown into ripples. It is shown, that for a given size of the drop, the fourth power of the width of the gap is proportional to the difference of temperature between the plate and the drop. A quantitative explanation of this result is given as due to the viscous flow of the steam outwards through the edge of the gap under the excess pressure which sustains the weight of the drop.

The experiments described above, were performed at the Laboratory of the Indian Association for the Cultivation of Science, and the author begs to record his deep thanks to Prof. C. V. Raman for his interest and help during the progress of the work.